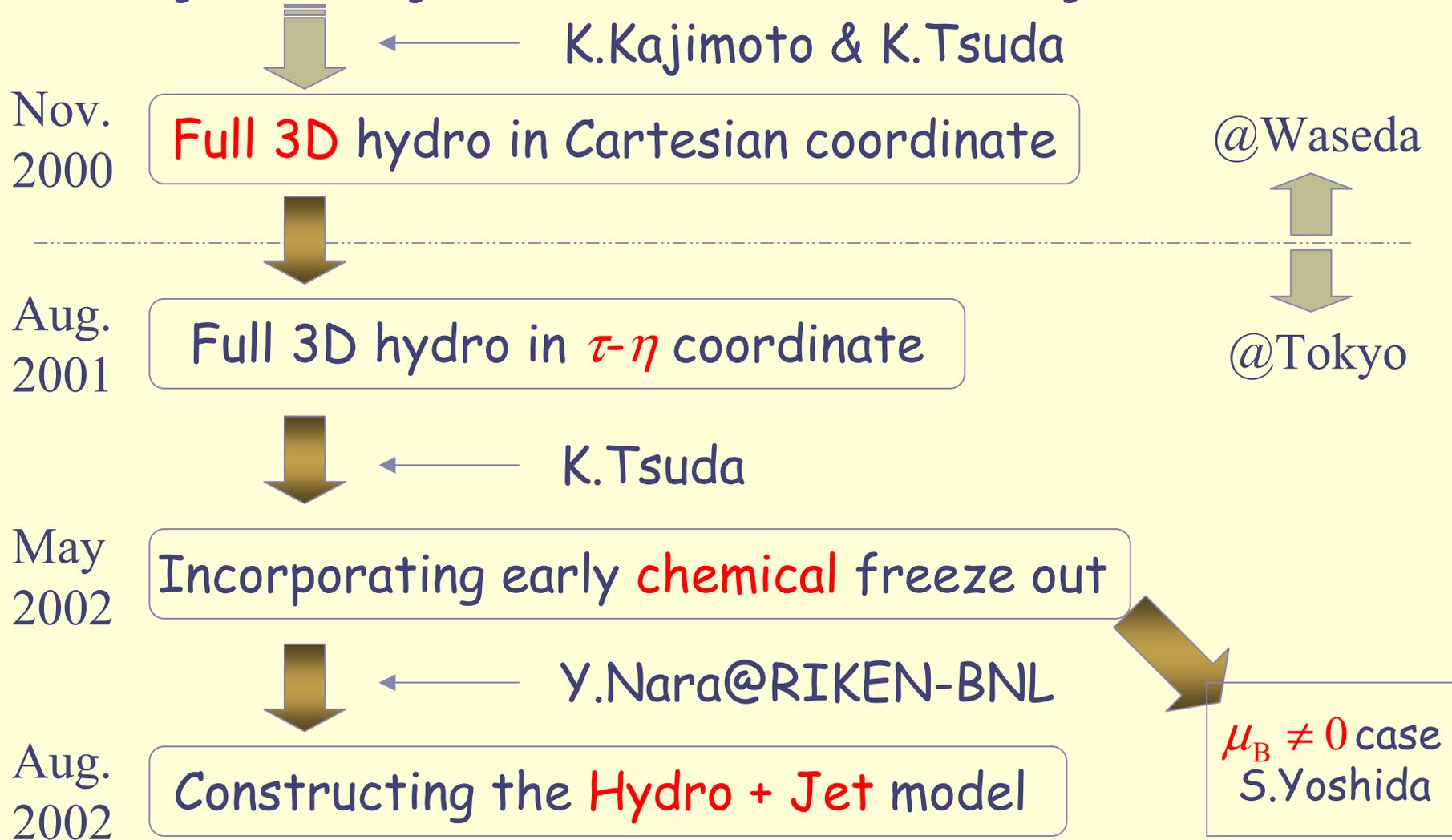


Recent Development of a Hydrodynamic Model by T.H.



Hydrodynamics with early chemical freeze out

Tetsufumi Hirano

Physics Dept., Univ. of Tokyo

Talk based on T.Hirano and K.Tsuda, nucl-th/0205043.

Collaborators: K.Tsuda, S.Yoshida

Introduction and Motivation

(See Yoshida-kun's talk)

$$T^{\text{ch}} \neq T^{\text{th}}$$

↑
Particle
ratio

↑
 p_T spectra
& HBT

Incorporate into
hydrodynamics
($\mu_B=0$)

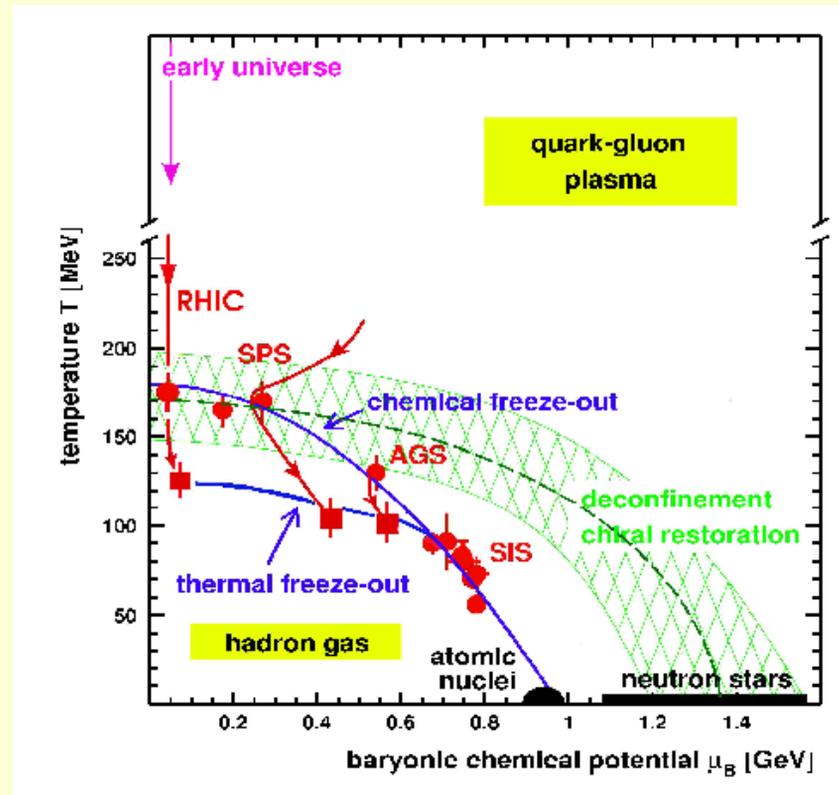
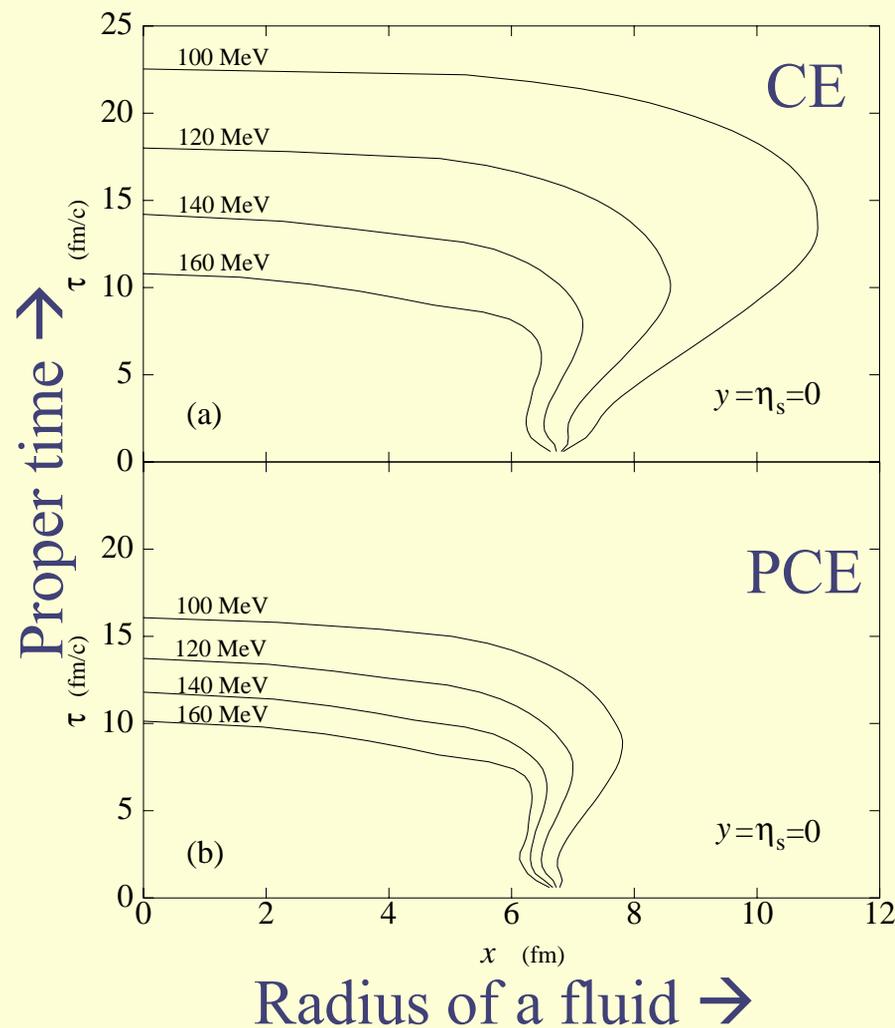
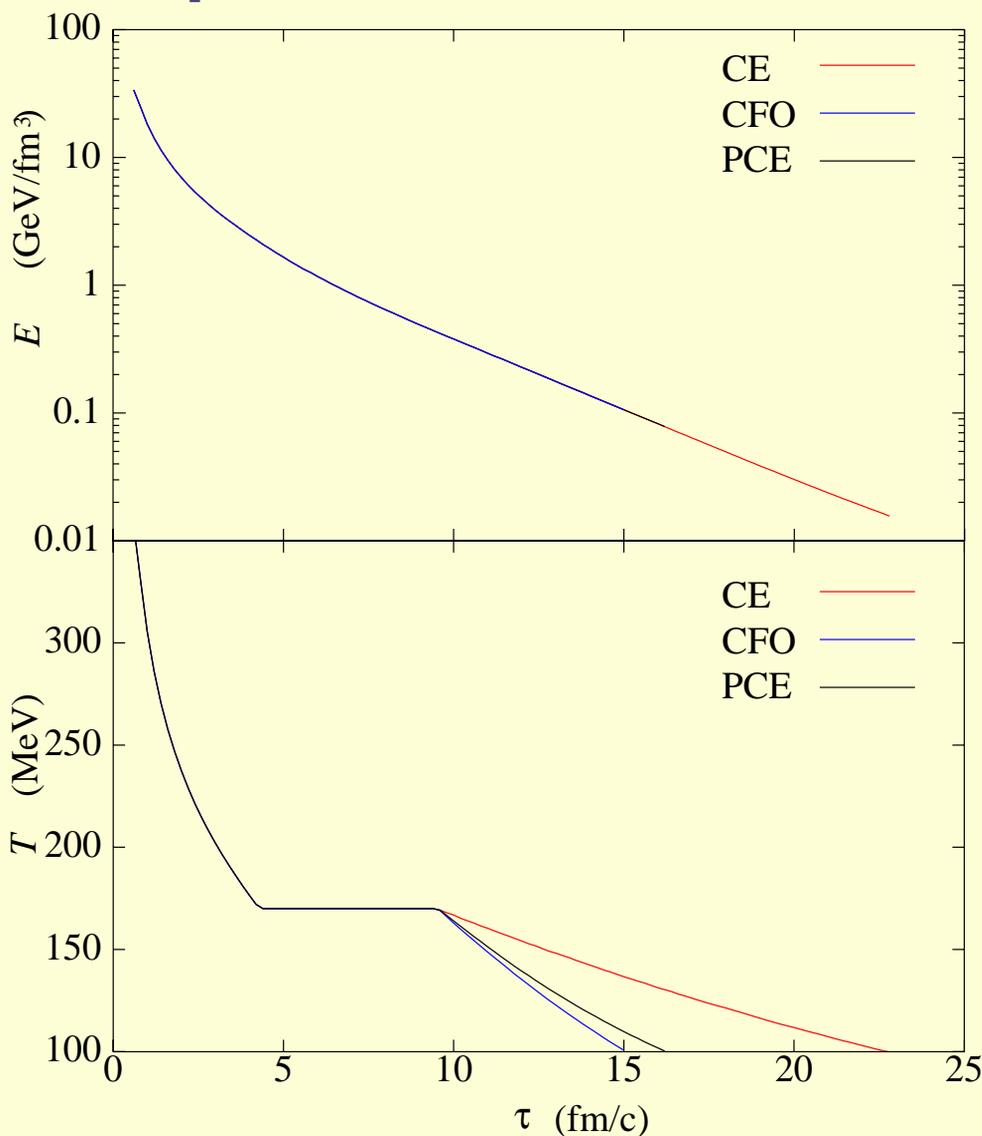
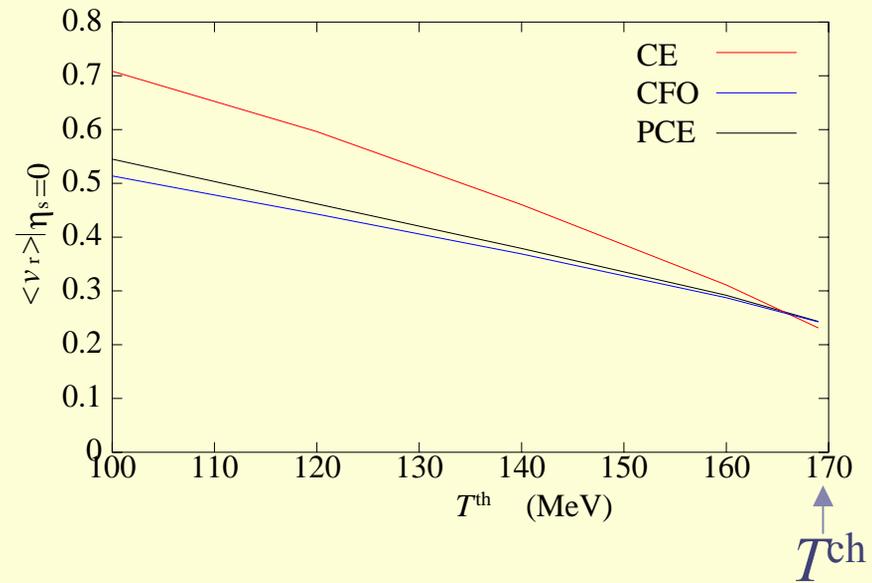
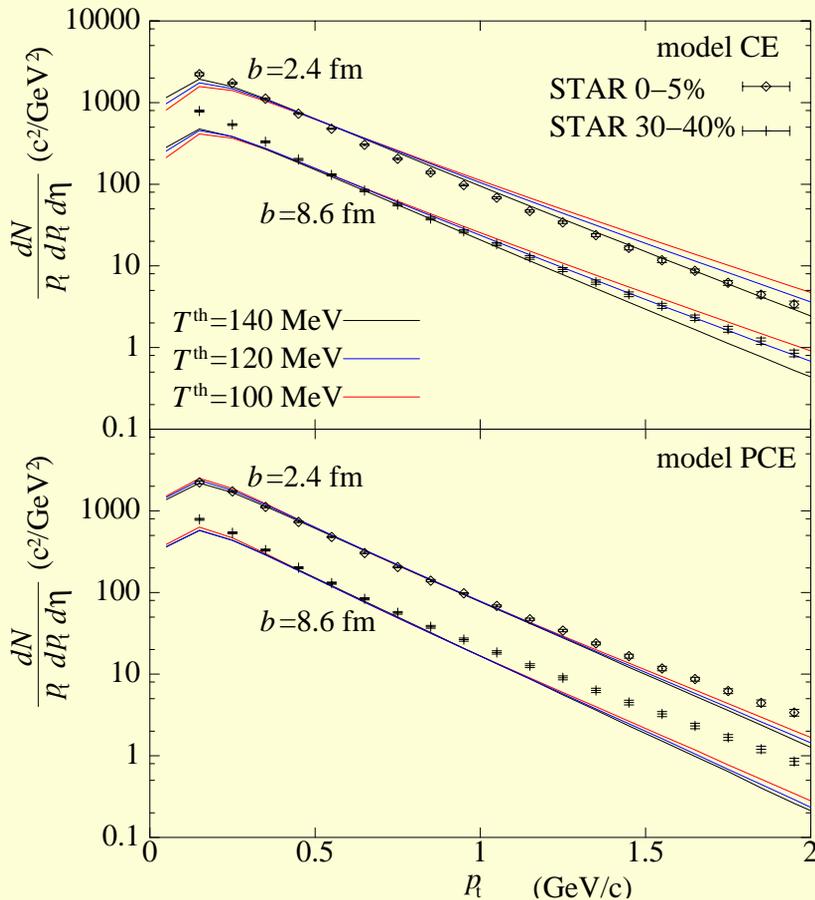


Figure from
U.Heinz, hep-ph/0109006.

Space-Time Evolution of Fluids



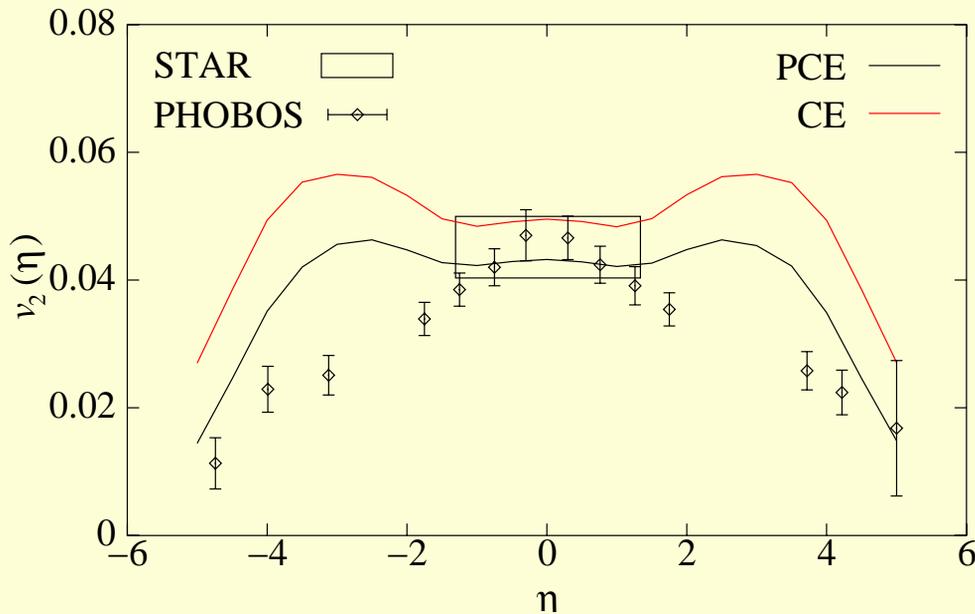
p_T Spectra of Charged Hadrons



$p_T > 1$ GeV/c
 \rightarrow hard contribution??

Data from STAR, PRL87,112303(2001);
 nucl-ex/0111004.

Elliptic Flow as a Function of Pseudorapidity



Our results ($T^{\text{th}}=140$ MeV):
 $0 < p_t < 2$ GeV/c, “min. bias”

PHOBOS:

All p_t , **accepted** data

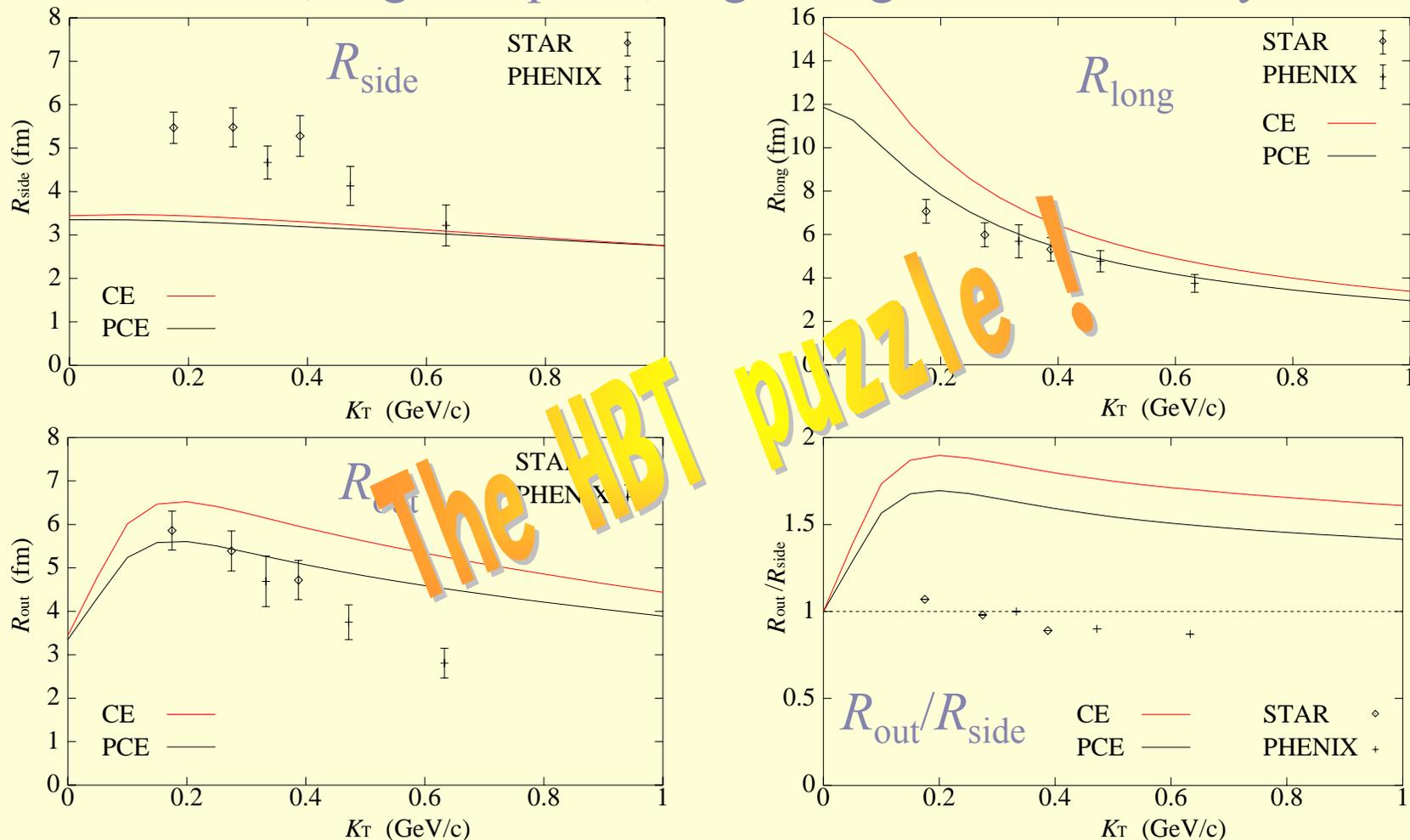
STAR:

$0.1 < p_t < 2$ GeV/c, min. bias

Elliptic flow is suppressed by
early chemical freeze-out!

K_T Dependence of HBT Radii

- $T^{\text{th}}=140$ MeV, negative pions, neglecting resonance decays.



Data from STAR, PRL87, 082301 (2001), PHENIX, PRL88, 192302 (2002).

Parton Energy Loss from the Hydro+Jet Model

Tetsufumi Hirano¹ and Yasushi Nara²

¹*Physics Dept., Univ. of Tokyo*

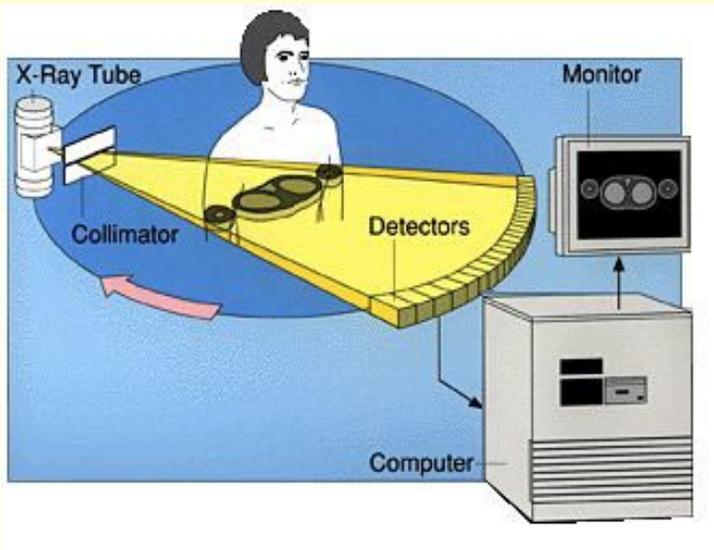
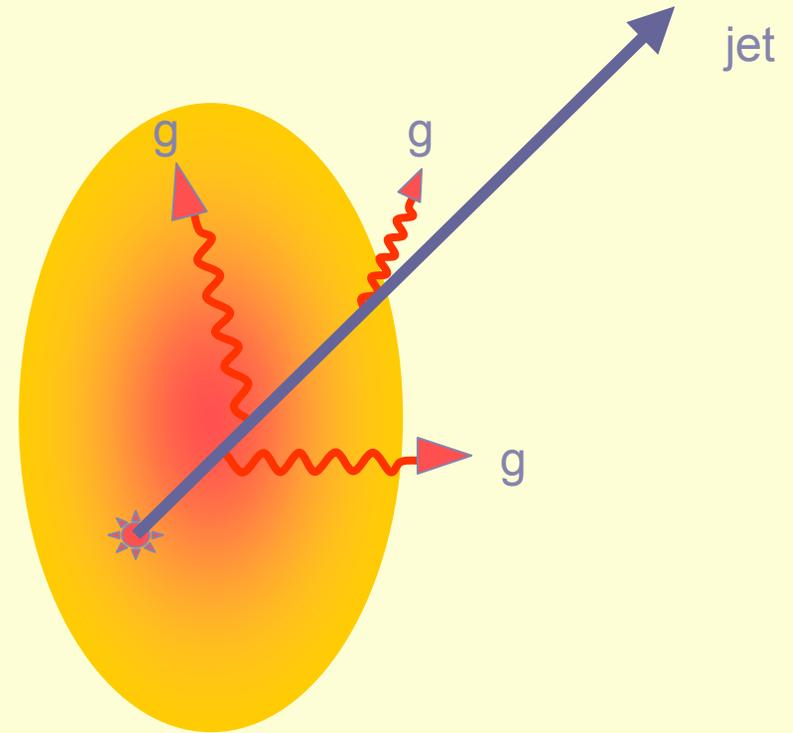
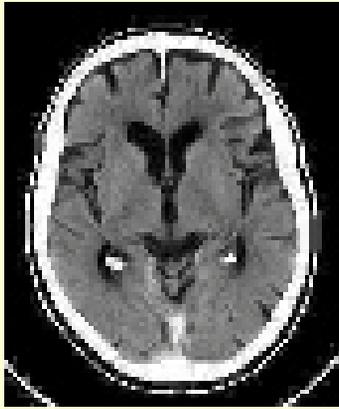


²*RIKEN BNL Research Center*



Talk based on T.Hirano and Y.Nara, hep-ph/0208029.

Jet Tomography



Does jet quenching contain information about QGP?

Figures from M.Gyulassy's talk

Why Jets at RHIC ?

Our definition

Jet: A parton with $p_T > 2 \text{ GeV}/c$
(often called “mini-jet”)

SPS

Pb+Pb@20 GeV

$$\sigma_{\text{in}} = 32 \text{ mb}$$

$$\sigma_{\text{jet}} = 0.1 \text{ mb}$$

$$N_{\text{coll}} = 923 (b=2 \text{ fm})$$

→ ~3 jets/event

RHIC

Au+Au@130 GeV

$$\sigma_{\text{in}} = 40 \text{ mb}$$

$$\sigma_{\text{jet}} = 10 \text{ mb}$$

$$N_{\text{coll}} = 1067 (b=2 \text{ fm})$$

→ ~250 jets/event

Au+Au@200 GeV

$$\sigma_{\text{in}} = 40 \text{ mb}$$

$$\sigma_{\text{jet}} = 20 \text{ mb}$$

$$N_{\text{coll}} = 1067 (b=2 \text{ fm})$$

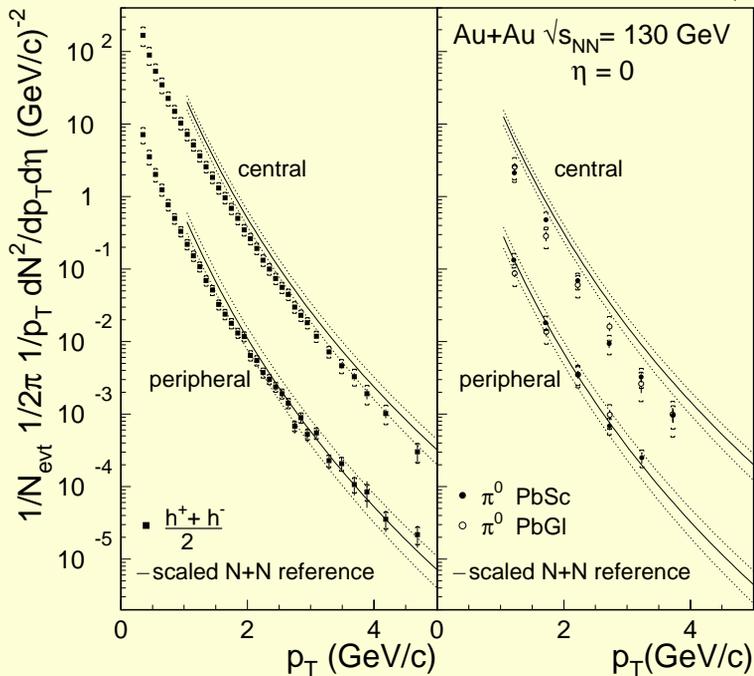
→ ~500 jets/event

Copious jets at RHIC !

σ_{jet} from PYTHIA 6.2 with $K=2$

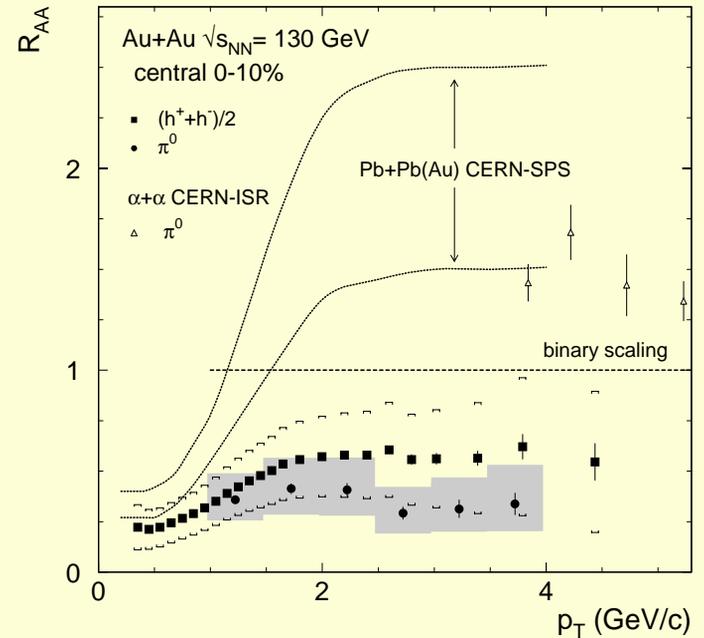
Exp. Data @ High p_T

K.Adcox et al. (PHENIX), PRL88, 022301.



$\langle b \rangle = 3.35 \text{ fm}$

$\langle b \rangle = 12.1 \text{ fm}$



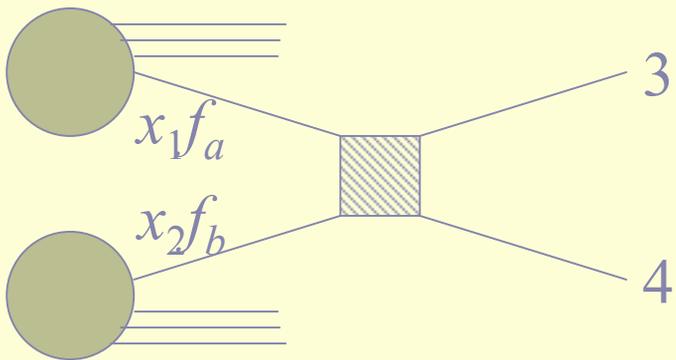
$$R_{AA}(p_T) = \frac{d^2 N^{A+A} / dp_T d\eta}{\langle N_{\text{binary}} \rangle d^2 N^{N+N} / dp_T d\eta}$$

First observation of jet quenching in H.I.C. !

Collinear Factorized Parton Model

$$\frac{d\sigma_{\text{jet}}}{dp_{\text{T}}^2 dY_3 dY_4} = K \sum_{a,b} x_1 f_a(x_1, Q^2) x_2 f_b(x_2, Q^2) \frac{d\sigma_{ab}}{d\hat{t}}$$

$x = p_i / p$: Momentum fraction of an initial parton $\left\{ \begin{array}{l} x_1 = \frac{p_{\text{T}}}{\sqrt{s}} (e^{Y_3} + e^{Y_4}) \\ x_2 = \frac{p_{\text{T}}}{\sqrt{s}} (e^{-Y_3} + e^{-Y_4}) \end{array} \right.$
 $f(x, Q^2)$: Parton distribution function (CTEQ5L)



Leading order QCD:

$$q + q' \rightarrow q + q', q + \bar{q} \rightarrow q' + \bar{q}'$$

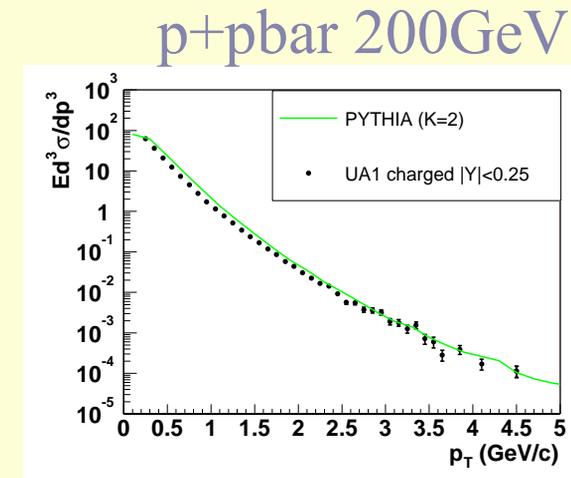
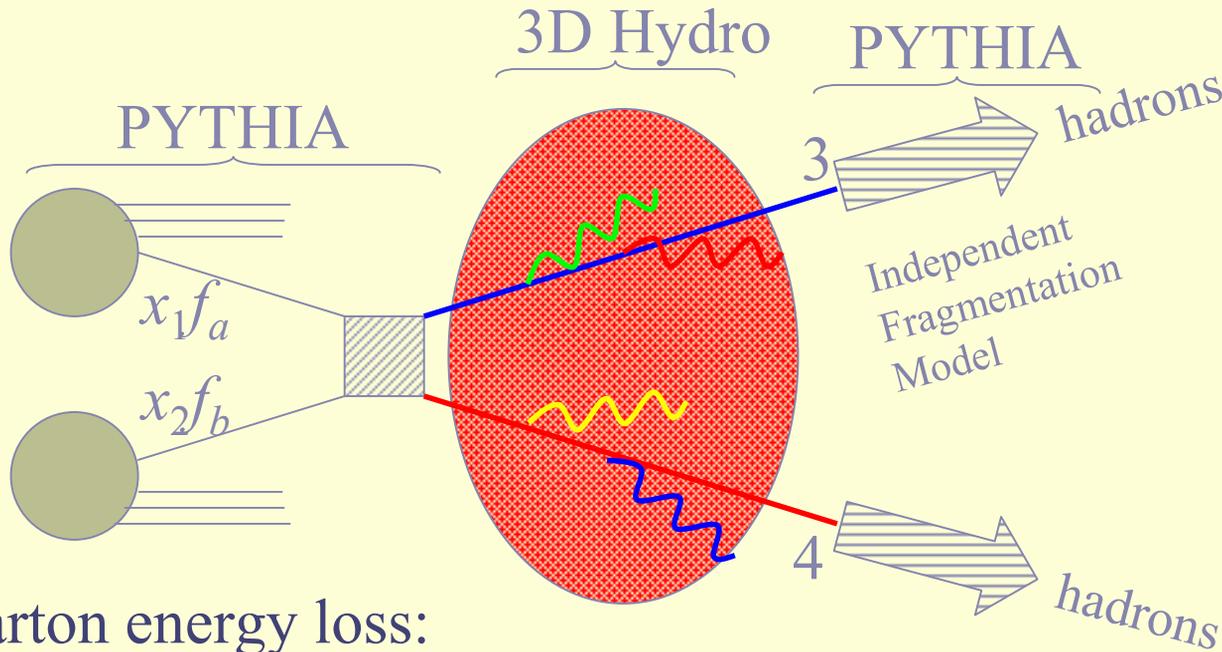
$$q + \bar{q} \rightarrow g + g, q + g \rightarrow q + g$$

$$g + g \rightarrow q + \bar{q}, g + g \rightarrow g + g$$

Dominant processes

See, e.g., Peskin & Schroeder, Chap.17.

Hydro+Jet Model



Parton energy loss:

$$\frac{dE}{dx} = \frac{\varepsilon}{\lambda} = \varepsilon \sigma \rho(\tau, r)$$

λ : mean free path

ρ : thermalized parton density

σ : parton-parton cross section

ε : energy loss per scattering

Parton density in the mixed phase

$$\rho = f_{\text{QGP}}(\tau, r) \rho(T_C)$$

$$f_{\text{QGP}} = \frac{E(\tau, r) - E_{\text{had}}}{E_{\text{QGP}} - E_{\text{had}}}$$

(Non-thermalized) Partons in Fluid Elements

PYTHIA gives us p_i^μ . $(x_i(0), y_i(0)) \leftarrow T(x+b/2, y)T(x-b/2, y)$
Partons travel **freely** till τ_0 (the initial time of the fluid).

Coordinate space

$\eta_s^i \equiv Y_i$ (Bjorken's ansatz
→ co-moving frame)

$$x_i(\tau + \Delta\tau) = x_i(\tau) + p_i^x \Delta\tau / E_T^i$$

$$y_i(\tau + \Delta\tau) = y_i(\tau) + p_i^y \Delta\tau / E_T^i$$

Momentum space

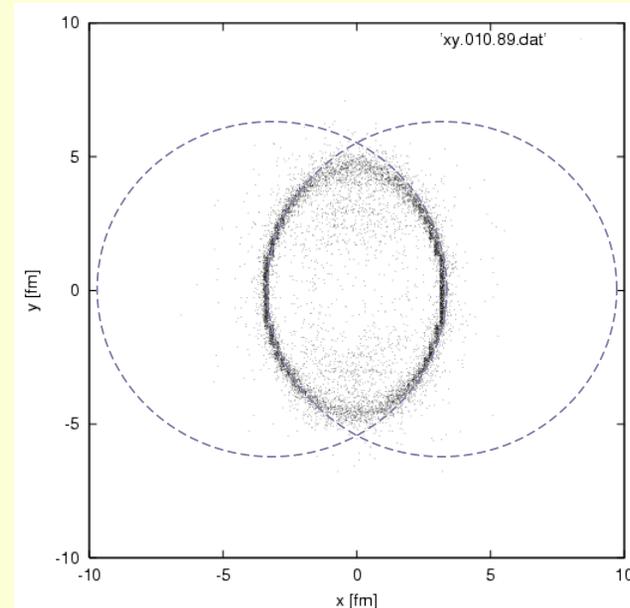
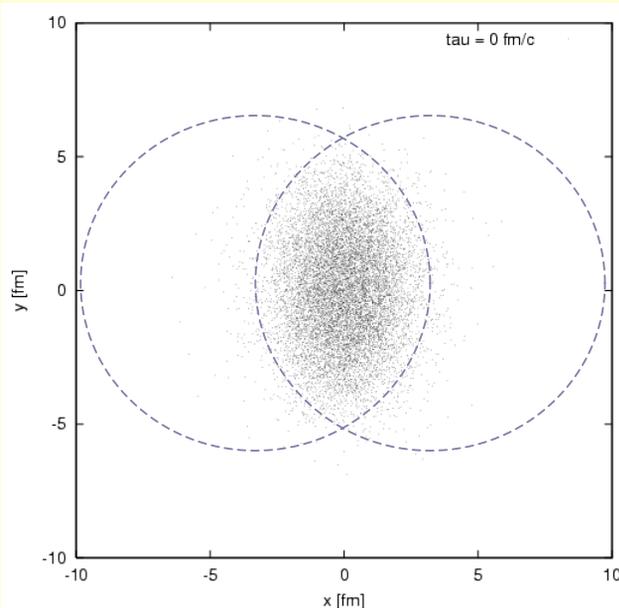
$$E_T^i(\tau + \Delta\tau) = E_T^i(\tau) - \frac{dE}{dx} \Delta x$$

$$p_T^i(\tau + \Delta\tau) = \sqrt{\left(E_T^i(\tau + \Delta\tau)\right)^2 - m_i^2}$$

$$p_x^i(\tau + \Delta\tau) = p_x^i(\tau) \frac{p_T^i(\tau + \Delta\tau)}{p_T^i(\tau)}$$

$$p_y^i(\tau + \Delta\tau) = p_y^i(\tau) \frac{p_T^i(\tau + \Delta\tau)}{p_T^i(\tau)}$$

Parton Evolution in the Transverse Plane

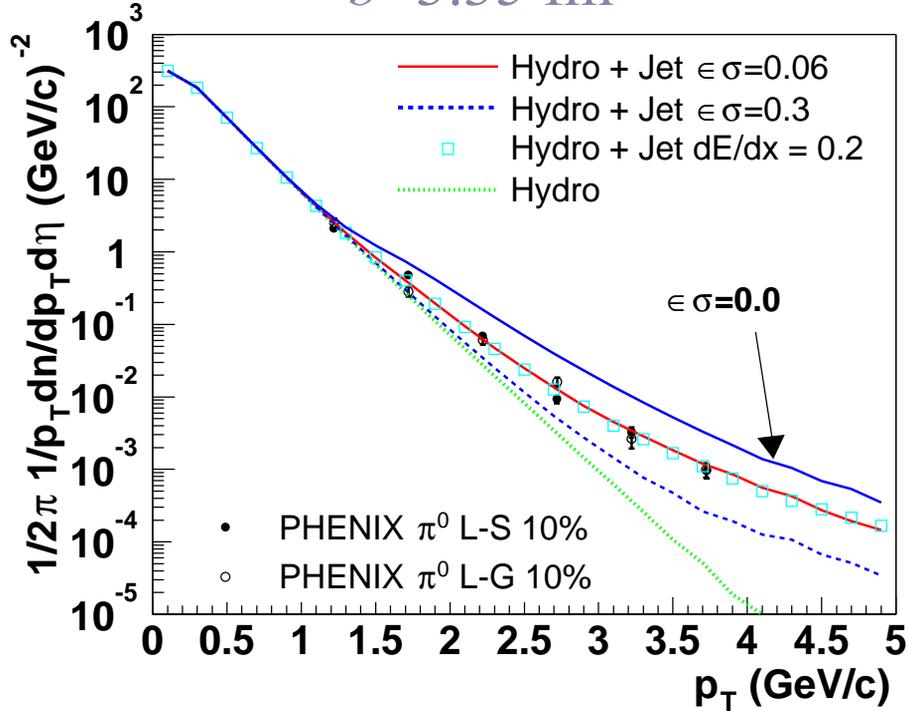


- Initial position of partons
→ Prop. to # of binary collisions
- Momentum distribution
(on-shell partons with $p_t > 2$ GeV/c) ← PYTHIA 6.2

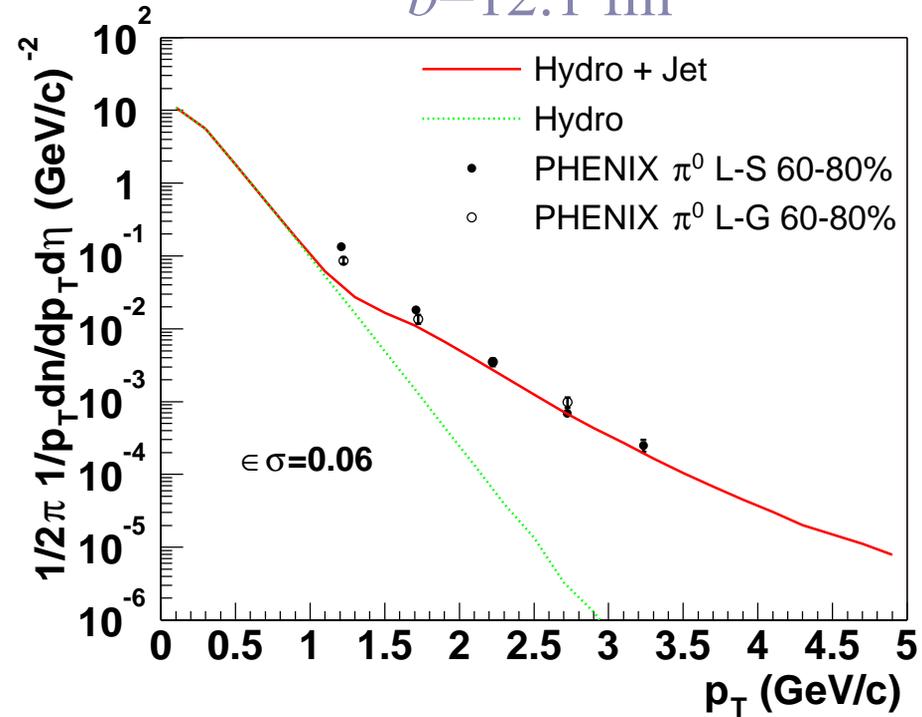
- Assuming partons move along classical paths
- Stop just after escaping from the QGP and mixed phases

π^0 Spectra @ High p_T

$b=3.35$ fm



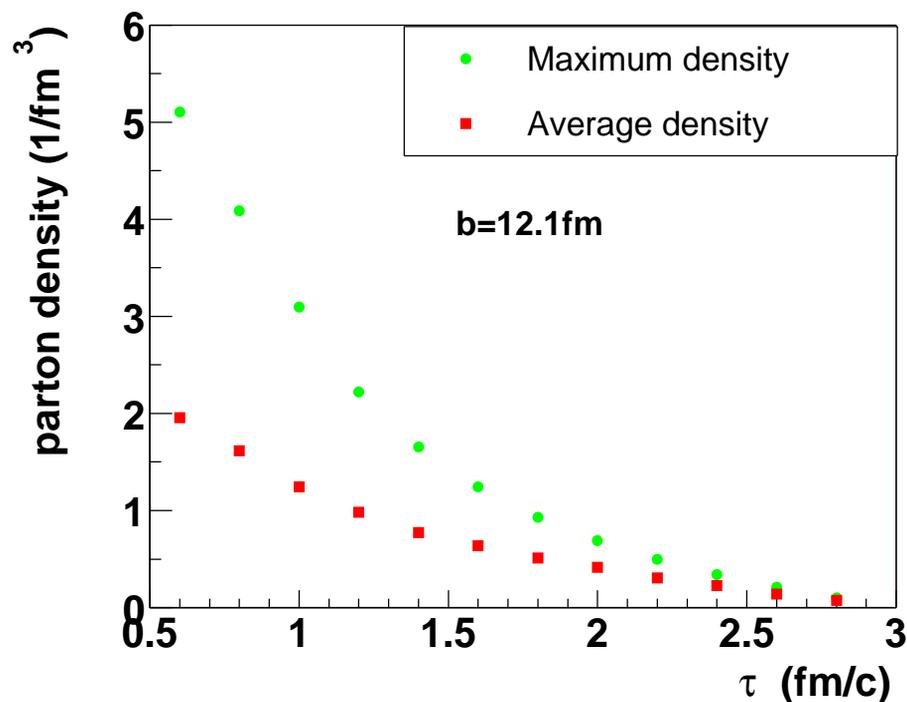
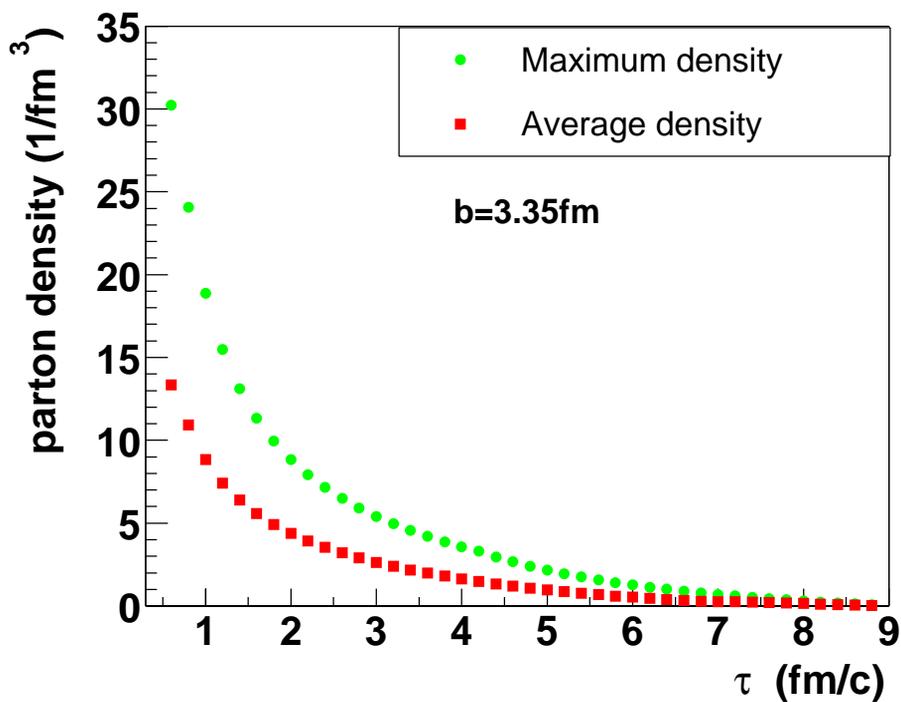
$b=12.1$ fm



$$\frac{dE}{dx} = 0.06 \rho \Leftrightarrow 0.2 \quad (\text{GeV/fm})$$

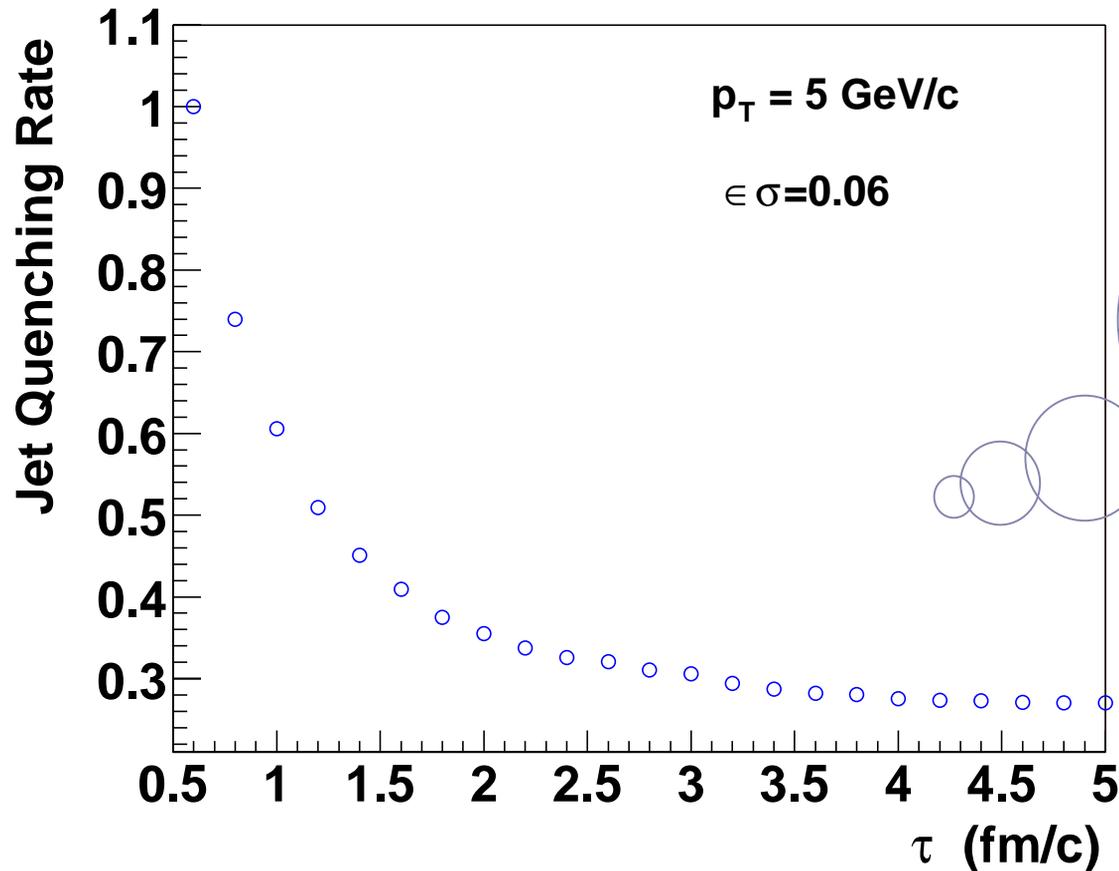
$$b=3.35 \text{ fm} \begin{cases} \Delta E = 550.55 \text{ GeV} \\ E_{\text{hydro}} = 21200 \text{ GeV} \\ \Delta E / E_{\text{hydro}} = 0.0259 \end{cases}$$

Time Evolution of Parton Density

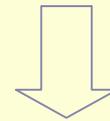


Strong longitudinal expansion \rightarrow Dilution of the QGP phase.

When Jet Quenching Happens?



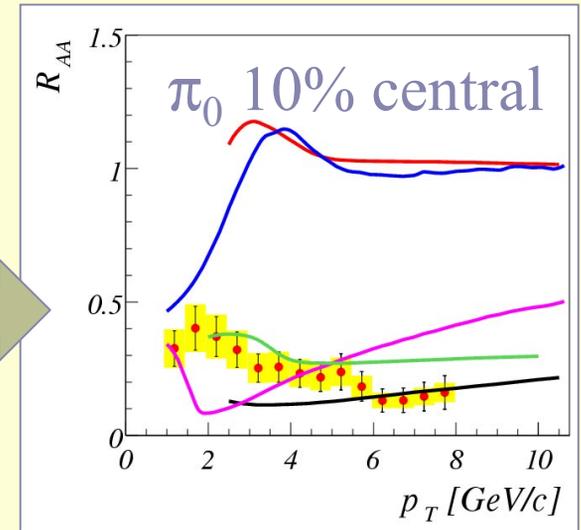
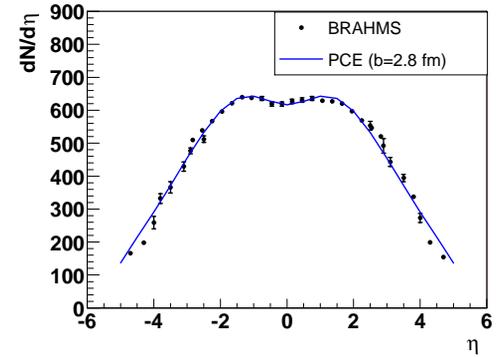
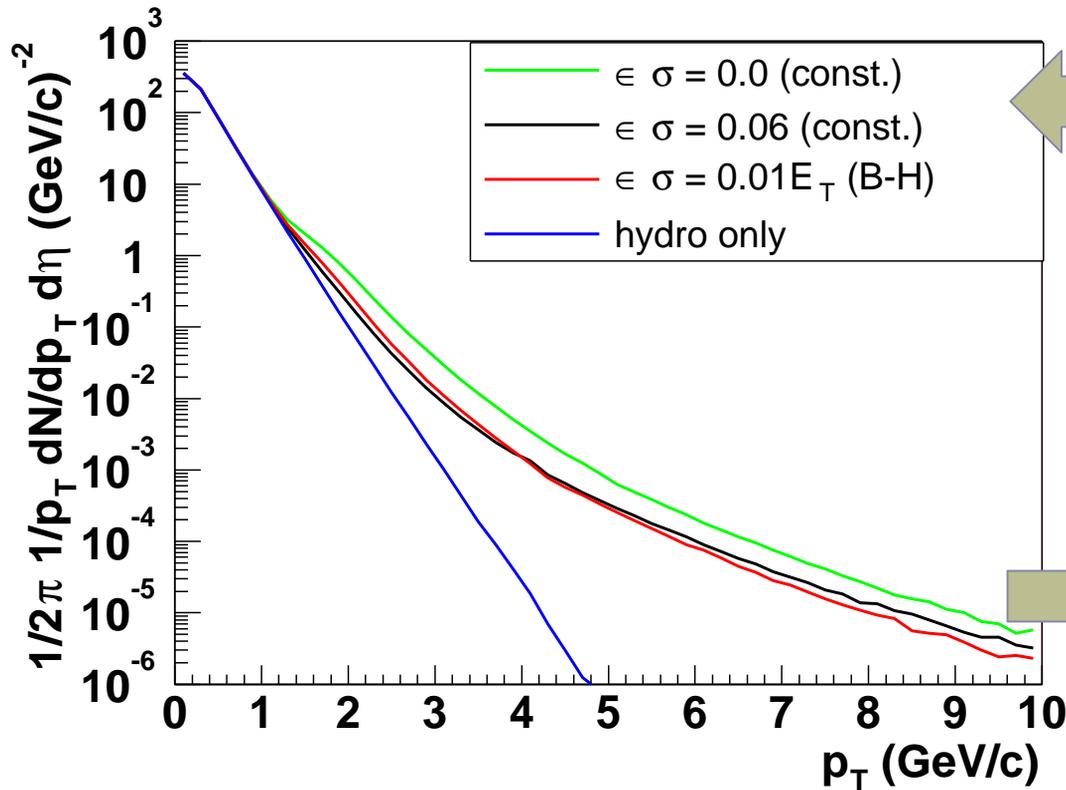
Suppression of
high p_T hadrons



Information on
the early stage
of **parton** phase!

$N(\tau)/N(\tau_0)$ at $p_T=5 \text{ GeV}/c$, $b=3.35 \text{ fm}$, $\epsilon\sigma=0.06 \text{ GeV fm}^2$

Jet Quenching @ 200 GeV



Simple model: $\epsilon\sigma=0.06 \text{ GeV fm}^2$
 Bethe-Heitler: $\epsilon\sigma=0.01E \text{ GeV fm}^2$

S.Mioduszewski (PHENIX)
 Talk @ QM2002, Nantes

What's New ?

1. Full 3D hydro in τ - η coordinate

- Rapidity dependence of
 - particle multiplicity
 - radial and elliptic flow
 - HBT radii

in non-central collisions

3. The Hydro + Jet model

- Quantitative estimation of jet quenching
 - Suppression of high p_t hadrons
 - Saturation of elliptic flow

2. Incorporating early chemical freeze out

- More realistic picture of hydrodynamic behavior
- Particle ratio $\leftarrow \mu_B \neq 0$

We are now almost ready to explore all hadronic observables in H.I.C within the only one tool.